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16. ABSTRACT

Available technical articles published during 1974, 1975, and 1976 on effects of heavy metals and toxic cations upon estuarine and marine flora and fauna were reviewed. For all articles, research effort generated by toxicant, by response parameter, and by major indicator organism assemblage was tabulated for field investigations and for laboratory studies. Most of the effort during this period was restricted to 5 metals (Zn, Hg, Cu, Cd, Pb) and 4 indicator groups (molluscs, teleosts, crustaceans, algae). Laboratory investigators devoted a major portion of their workload to uptake, retention, and translocation studies, followed by studies on survival, on growth and development, reproduction, food chain transfer, behavior, respiration, body fluid chemistry, histology, and others, in that sequence. Results of field studies were confined almost exclusively to acquisition of data on baseline elemental composition and accompanying biotic and abiotic modifiers.

Apparent limitations and deficiencies of current projects on biological effects assessment of metals and toxic cations in marine environments were presented and discussed. Suggestions were offered on direction and emphasis of future research in this subject area.

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TOXIC CATIONS AND MARINE BIOTA: ANALYSIS OF RESEARCH EFFORT DURING THE THREE-YEAR PERIOD 1974-1976[1]

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INTRODUCTION

There is a growing body of literature on biological and toxicological effects of heavy metals and other cations to marine biota (Waldichuk, 1974; Bernhard and Zattera, 1975; Eisler and Wapner, 1975). This increase, which shows no sign of abatement, is probably attributable to recent technological advances in atomic absorption spectrophotometry, neutron activation analyses, and anodic stripping voltometry, as well as to the greater availability of instrumentation to marine scientists. However, the research approaches employed to-date on evaluation of effects of toxic cations on estuarine and oceanic flora and fauna are both numerous and disparate. Awareness of the many factors involved in assessment of biological properties of chemical pollutants in general, and cations in particular, is essential for the establishment and implementation of meaningful marine water quality standards. This account categorizes available technical articles on effects of toxic cations to marine organisms that were published during the three-year period 1974-1976. Specifically, 233 individual contributions are identified by effort generated by cation, by major indicator organism assemblage and by response parameter. Research effort is also identified by

[1]Note: Due to the abundance of information presented in Appendix I, the numerical system of referencing will be used in that section.

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laboratory study or by field investigation. Major trends are tabulated, research gaps are identified, and suggestions are offered on direction and emphasis of future research in this subject area.

ANALYSIS OF RESEARCH EFFORT

By Cation

During 1974-1976, marine biological effects studies were conducted with 41 different heavy metals and cations (Table 1). Data on sodium, potassium, and calcium were especially abundant, but these were arbitrarily excluded from Table 1. About 62% of the total effort was contributed to studies on five metals: zinc, mercury, copper, cadmium, and lead. Another 25% was confined to the group consisting of iron, manganese, chromium, nickel, silver, cobalt, and arsenic. The remaining 29 elements constituted about 13% of all effort.

Of the total cation effort, laboratory studies conprised about 48% and field investigations 52% (Table 1). The average laboratory study contained 2.09 cations/reference; this value was substantially higher (3.16) for field investigation reports. For all references, the average number of cations per reference was 2.54. When compared to laboratory studies a slightly higher percentage of the field effort was devoted to Zn, Pb, and Ni, and a lower percentage to Co; otherwise, effort for individual cations was within 1% for both categories.

It is remarkable that no research effort was recorded during the 1974-1976 interval on cations of known high toxicity to aquatic biota, *viz* gold, platinum, tin, and tungsten. Elements of potential environmental concern from the actinide series, especially californium and neptunium, and practically the entire lanthanide group were also neglected.

By Indicator Assemblage

Organisms from 22 major marine taxonomic groups, representing more than 200 different species, were used to evaluate toxic cation effects during the period 1974-1976 (Table 2). About 76% of the total effort was restricted to four groups: crustacea, mollusca, algae, and fish. An additional 11% was contributed by annelids, bacteria, coelenterates, and echinoderms. The remaining 14 groups comprised about 13% of the total indicator organism effort.

TABLE 1. Toxic cations and marine biota: cation effort from 233 papers published during the interval 1974-1976 inclusive. N=number of papers referring to specific cation; %=percent of total responses contributed by individual cations

	Total		Laboratory Studies		Field Studies	
	N	%	N	%	N	%
Zinc (Zn)	84	14.2	38	6.4	46	7.8
Mercury (Hg)	78	13.2	42	7.1	36	6.1
Copper (Cu)	75	12.7	37	6.2	38	6.4
Cadmium (Cd)	75	12.7	35	5.9	40	6.8
Lead (Pb)	54	9.1	22	3.7	32	5.4
Iron (Fe)	25	4.2	10	1.7	15	2.5
Manganese (Mn)	23	3.9	10	1.7	13	2.2
Chromium (Cr)	22	3.7	11	1.9	11	1.9
Nickel (Ni)	22	3.7	6	1.0	16	2.7
Silver (Ag)	20	3.4	9	1.5	11	1.9
Cobalt (Co)	17	2.9	13	2.2	4	0.7
Arsenic (As)	14	2.4	6	1.0	8	1.3
Magnesium (Mg)	10	1.7	7	1.2	3	0.5
Plutonium (Pu)	10	1.7	4	0.7	6	1.0
Strontium (Sr)	5	0.8	4	0.7	1	0.2
Selenium (Se)	5	0.8	3	0.5	2	0.3
Cesium (Cs)	5	0.8	3	0.5	2	0.3
Polonium (Po)	5	0.8	1	0.2	4	0.7
Ruthenium (Ru)	4	0.7	3	0.5	1	0.2
Vanadium (V)	4	0.7	2	0.3	2	0.3
Boron (B)	3	0.5	3	0.5	0	0.0
Americium (Am)	3	0.5	1	0.2	2	0.3
Antimony (Sb)	3	0.5	0	0.0	3	0.5
Technetium (Tc)	2	0.3	2	0.3	0	0.0
Thallium (Tl)	2	0.3	2	0.3	0	0.0
Aluminum (Al)	2	0.3	1	0.2	1	0.2
Cerium (Ce)	2	0.3	1	0.2	1	0.2
Molybdenum (Mo)	2	0.3	1	0.2	1	0.2
Yttrium (Y)	2	0.3	1	0.2	1	0.2
Bismuth (Bi)	2	0.3	0	0.0	2	0.3
Titanium (Ti)	2	0.3	0	0.0	2	0.3
Beryllium (Be)	1	0.2	1	0.2	0	0.0
Germanium (Ge)	1	0.2	1	0.2	0	0.0
Rubidium (Rb)	1	0.2	1	0.2	0	0.0
Silicon (Si)	1	0.2	1	0.2	0	0.0
Europium (Eu)	1	0.2	0	0.0	1	0.2
Niobium (Nb)	1	0.2	0	0.0	1	0.2
Radium (Ra)	1	0.2	0	0.0	1	0.2
Rhodium (Rh)	1	0.2	0	0.0	1	0.2
Thorium (Th)	1	0.2	0	0.0	1	0.2
Zirconium (Zr)	1	0.2	0	0.0	1	0.2
TOTAL	592	100.0	282	47.8	310	52.6

TABLE 2. Research effort expended on biological effects of cations, by indicator organism groups, during the interval 1974-1976 inclusive. N=number of 233 published papers referring to a specific indicator group; %=percent of all responses (347) contributed by individual groups

	Total[a]		Laboratory Studies[b]		Field Studies[c]	
	N	%	N	%	N	%
Mollusca	78	22.4	38	11.0	40	11.4
Fish	69	19.8	27	7.8	42	12.0
Crustacea	66	19.0	41	11.8	25	7.2
Algae	51	14.7	33	9.5	18	5.2
Annelida	15	4.3	14	4.0	1	0.3
Mammals	11	3.2	0	0.0	11	3.2
Echinodermata	10	2.8	5	1.4	5	1.4
Bacteria	8	2.3	5	1.4	3	0.9
Higher Plants	8	2.3	0	0.0	8	2.3
Tunicata	6	1.8	2	0.6	4	1.2
Coelenterata	6	1.7	5	1.4	1	0.3
Elasmobranchs	4	1.2	0	0.0	4	1.2
Insecta	3	0.9	0	0.0	3	0.9
Protozoa	2	0.6	2	0.6	0	0.0
Birds	2	0.6	0	0.0	2	0.6
Plankton	2	0.6	0	0.0	2	0.6
Turbellaria	1	0.3	1	0.3	0	0.0
Nematoda	1	0.3	1	0.3	0	0.0
Platyhelminthes	1	0.3	1	0.3	0	0.0
Bryazoa	1	0.3	1	0.3	0	0.0
Fungi	1	0.3	1	0.3	0	0.0
Chaetognaths	1	0.3	0	0.0	1	0.3
	347	100.0	177	51.0	170	49.0

[a] 233 references; 347 citations=1.49 indicators/reference
[b] 135 references; 177 citations=1.31 indicators/reference
[c] 98 references; 170 citations=1.74 indicators/reference

There were marked differences between laboratory and field studies in selection of indicators. For example, no laboratory studies were conducted on marine mammals, higher plants, elasmobranchs, insects, birds, plankton, and chaetognaths; whereas, field studies did not include protozoa, turbellarians, nematodes, platyhelminthids, bryozoans, or fungi as indicators. Only 9 of the 22 indicator groups were studied under both laboratory and field conditions: crustacea, mollusca, algae, fish, annelids, bacteria, coelenterates, echinoderms, and tunicates. Of these only crustacea, mollusca, algae and fish contributed significantly to the total research effort. Reports arising from field investigations cited a greater average number of indicator organism groups per reference than laboratory studies: 1.74 *vs.* 1.31; for all studies this was 1.49.

By Response Parameter

Criteria used by investigators during the 3-year period 1974-1976 to evaluate effects of heavy metals and other cations to selected indicator organism groups are listed by cation, by reference, and by laboratory or field effort (see Appendix 1). Factors modifying the major effect studied are also listed when appropriate.

More than 37% of the total response parameter effort was devoted to effects of modifiers (see Appendix 1); in many cases these modifiers could alter measured responses by an order of magnitude, or more. Thus, biotic modifiers which affected cation residue content in field collections of organisms included: age, size, body weight, sex and sexual condition of the organism; feeding frequency, diet composition, and feeding niche in water column; metabolism, organism complexity, and selective tissue specificity of cations; general condition of the animal, and whole body elemental composition. Abiotic modifiers affecting residues in field biota included: geographic and spatial factors such as distance from point source, latitudinal, seasonal, monthly, and yearly variations; physical factors such as temperature, salinity, turbidity, water depth, sediment particle size, and geothermal and tectonic activity; inorganic and organic composition of water column and sediment substrate; selective accumulation of different chemical species; and errors introduced in sampling *i.e.* Cu and Zn contamination of molluscs from a water pump. As was true for field studies, many factors strongly modified uptake, retention, and translocation mechanisms of cations under controlled laboratory conditions. These included temperature, salinity, light intensity, turbidity, size of particulates, season of year, toxicant concentration and mode of administration; age, size, sexual condition, molting state (in crustaceans), tissue specificity and bacterial

interaction effects; physical and chemical composition of sediment substrate; and levels of inorganics and organics in water column. Differential uptake of chemical species was also important, with marked variations evident for chemical species of Cd, Cr, Cu, Hg, Ni, Ru, Se, Zn; variations were partly attributable to differences in anion constituent, partly to organic *vs* inorganic forms, and partly to discrimination among isotopes. Similar cases, on a more limited basis, are made for factors modifying survival, growth, and development (including photosynthesis), and reproduction.

Response parameter data are summarized in Table 3. It is clear from these data that the major emphasis in field studies is on collection of baseline residue data; for laboratory studies it is on bioaccumulation, survival, growth, reproduction, food chain dynamics, behavior, respiration, biochemistry and hematology, histology, and others, in that order. Publications resulting from field studies, when compared to laboratory investigations contained about twice the number of response parameters per reference: 7.15 *vs* 3.71 (Table 3). But this statistic may reflect the extensive elemental analyses conducted on field collections comprised of numerous species.

Analysis of cations as a function of response parameter indicates that greatest effort for all studies was devoted to Hg, Cd, Cu, Zn, Pb, Cr, Fe, and Mn, in that sequence. These data are not shown, but they do not differ significantly in ranking from those shown previously in Table 1.

For all studies, indicator groups used most frequently for response parameters were molluscs (30.7%), fishes (20.9%), algae (14.8%), crustaceans (10.1%), mammals (5.2%), annelids (3.8%), and echinoderms (3.5%). Molluscs accounted for 30.7% of the total response parameter effort compared to only 22.4% when listed by citation (Table 2). For crustaceans the response parameter effort was 10.2%, a drop from 19.0% when listed by citation (Table 2); none of the other indicator assemblages showed major directional trends when compared to Table 2.

DISCUSSION AND RECOMMENDATIONS

Continuing research effort appears warranted on cations with known deleterious effects to human health, especially mercury, cadmium, lead, arsenic, and selenium, and on metals of proven high toxicity at comparatively low concentrations to marine biota, *viz* copper, chromium, silver, and to a lesser extent, zinc and nickel. Increased emphasis should be directed to studies on environmental aspects of transuranics in marine ecosystems, especially plutonium, americium, curium, neptunium, and other alpha emitters. These will assume increasing

TABLE 3. Summary of laboratory and field research effort on effects of toxic cations to marine biota, by response parameters. Values are in % of total effort (N=1202)

	Laboratory Studies[a]	Field Studies[b]	Total[c]
Baseline residue data	0.0	35.4	35.4
-modifiers	0.0	19.5	19.5
Uptake, retention, translocation	8.7	0.0	8.7
-modifiers	8.8	0.0	8.8
Survival	4.9	0.0	4.9
-modifiers	2.3	0.0	2.3
Growth, development, photosynthesis	3.7	0.6	4.3
-modifiers	2.0	0.0	2.0
Reproduction	2.1	0.4	2.5
-modifiers	0.9	0.0	0.9
Food chain transfer	2.3	0.6	2.9
Behavior	1.1	0.0	1.1
Respiration	1.1	0.0	1.1
Role in cycling	0.0	1.1	1.1
Enzymes, proteins, blood chemistry	0.9	0.0	0.9
Histology, pathology	0.9	0.0	0.9
Seasonal dynamics	0.8	0.0	0.8
Osmoregulation	0.4	0.0	0.4
Health Hazard	0.2	0.2	0.4
Morphology	0.3	0.0	0.3
Others	0.3	0.5	0.8
	41.7	58.3	100.0

[a] 135 references; 501 citations=3.71 response parameters/reference
[b] 98 references;701 citations=7.15 response parameters/reference
[c] 233 references; 1202 citations=5.16 response parameters/reference

importance if proposed construction of coastal nuclear steam electric stations is implemented. Some effort should be devoted to platinum in the marine environment, since this metal could become an important contaminant owing to its use in automobile emission control devices. Other potentially harmful cations about which little is known regarding sources, distribution, fate, and effects in marine ecosystems include tungsten, thallium, tin, and beryllium; research on these cations and their salts clearly merit additional effort. For all studies the chemical species of the cation should be identified together with the methylation potential and relation between organic and inorganic forms, if possible. Results from field investigations would be substantially enhanced with inclusion of data on anthropogenic loadings of cations and other potential toxicants to the study area; amounts of these same materials normally contributed from geological and other sources should also be referenced.

Greater use of marine mammals, fish-eating birds, higher plants, and bacteria in laboratory studies on effects of toxic cations is suggested, as is continued use of these groups in field investigations. Ship-board scientists should strive to integrate their efforts with ongoing comprehensive monitoring programs typical of those established by International Commissions on whaling, salmon, tuna, and seabirds. All studies should continue to utilize molluscs, crustaceans, fishes, and algae as indicators of environmental stress and to explore possibilities of other groups, especially coelenterates, annelids, and echinoderms, which seem to show promise of becoming suitable indicators. Since conservation and maintenance of marine resources entails knowledge of toxicant fluxes, including effects on several life stages of economically important species and their food organisms, it behooves the investigator to select appropriate indicators and developmental stages for purposes of testing and analyses. Where human health is a prime factor, it appears reasonable to prioritize data collections of metals in edible flesh of marine products of commerce, especially teleosts, bivalve molluscs, and decapod crustaceans. Metal concentrations in viscera and other "scrap" marine biota now processed into meal supplements for domestic poultry, swine, and cattle may indirectly affect health; accordingly, residues in these products should also be determined and the efficiency of food chain transfer established. A word of caution: the number of species now utilized or recommended as indicators of marine water quality is proliferating rapidly, yet essential information on baseline physiology, metabolism, behavior, and other indices of well-being is either limited or missing. This is in sharp contrast to the health sciences, which annually expends substantial funds on normal physiology and behavior of small mammals used

in research--especially rodents, felines, canines, and primates. It is apparent that additional research is required on "unstressed" marine indicator groups, with emphasis on only a few selected species.

As recently as 20 years ago there were comparatively few researchers evaluating biological effects of metals in marine waters and most of this early effort was restricted to effects on survival and growth. Substantial advances have been made since, but, in perspective, response parameters currently used to measure cation-induced stress are still somewhat limited. For example, effects at the cellular and sub-cellular levels are scarce or absent while those on residues and biomagnification receive a disproportionate share of research budgets. Towards this end, greater effort could be devoted to histopathological, biochemical, and behavioral parameters as early indicators of growth impairment, reproductive success, survival, metabolic imbalance, and alterations in community structure. These, however, must of necessity be tied to data on survival, growth, residue levels, metabolism, and general well-being.

Finally, it is strongly recommended that interaction effects of the cation under study should be evaluated with due consideration of other constituents in the waste stream. It is well-established that coastal waters adjacent to large population centers receive a variety of wastes as a result of domestic, agricultural, municipal, and industrial operations. Some of these components are harmful to marine biota, but their toxic action is not necessarily predictable on a simple additive basis; some may act synergistically, others antagonistically. Toxicological evaluation of complex wastes discharged into marine environments is still an infant science. However, a multiparametric approach is now routinely employed by industrial toxicologists, physicians, and others concerned with the health of persons who work with dangerous or hazardous materials. This approach is based on the acceptable hypothesis that metabolic disturbances have a far greater probability of detection if a number of physiological and biochemical parameters are simultaneously determined and plotted. This technique appears to hold substantial promise as a predictive tool for diagnosis of metabolic derangement in marine indicator species long before obvious morphological or behavioral effects become evident. With the multiparametric approach, laboratory-oriented scientists may find it profitable to devote an increasing proportion of their work load to assessment of real world concentrations and combinations of actual or potential toxicants, whereas field workers may find similar rewards in expansion of their baseline residue data effort to include physiological indications of environmental perturbation.

SUMMARY

Available technical articles published during 1974, 1975, and 1976 on effects of heavy metals and toxic cations upon estuarine and marine flora and fauna were reviewed. For all articles, research effort generated by toxicant, by response parameter, and by major indicator organism assemblage was tabulated for field investigations and for laboratory studies. Most of the effort during this period was restricted to 5 metals (Zn, Hg, Cu, Cd, Pb) and 4 indicator groups (molluscs, teleosts, crustaceans, algae). Laboratory investigators devoted a major portion of their workload to uptake, retention, and translocation studies, followed by studies on survival, on growth and development, reproduction, food chain transfer, behavior, respiration, body fluid chemistry, histology, and others, in that sequence. Results of field studies were confined almost exclusively to acquisition of data on baseline elemental composition and accompanying biotic and abiotic modifiers.

Apparent limitations and deficiencies of current projects on biological effects assessment of metals and toxic cations in marine environments were presented and discussed. Suggestions were offered on direction and emphasis of future research in this subject area.

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APPENDIX I

Response parameters used to evaluate effects of toxic cations to marine biota. Groupings are by indicator organisms, by laboratory studies, and by field investigations.

ALGAE

Laboratory Studies

Survival: Cd (20); Cu (20); Hg (20); Pb (20, 93, 94)
-Modifier:
--resistance of lab strains *vs* wild cells: Pb (20)
Food chain transfer: Cu (181)
Respiration: As (25); Hg (150)
Photosynthesis and Growth: B (12, 117); Cd (20); Co (26); Cs (199); Cu (20, 32, 102, 138, 150, 181); Ge (204); Hg (20, 52, 53, 107, 150); Pb (20, 93, 94); Tl (150); Zn (32, 102, 199)
-Modifiers:
--chemical species: Cu (200)
--prior exposure affects growth: B (12)
--inorganics: Cu (32); Ge (204); Hg (150); Zn (32)
--essential trace: B (117); Co (26)
--developmental stage: Pb (93)
--temperature: Cs (199); Zn (199)
--salinity: Cs (199); Zn (199)
--organics: Cu (200)
--pH: Cu (200)
--species specific: Ge (204)
Uptake, retention, translocation: Cd (44, 211); Cs (199); Ce (176); Co (7, 123); Cr (123); Cu (102, 200); Fe (123, 234); Pb (196); Mn (123, 176); Hg (52); Mo (153); Pu (87, 88); Rb (153); Ru (87, 88); Ag (164); Tc (87, 88); Zn (11, 123, 199, 234)
-Modifiers:
--chemical species: Cd (44)
--particle size: Pu (88); Ru (88)
--growth stage: Cd (44); Fe (234); Zn (234)
--temperature: Mo (153); Rb (153); Zn (199)
--season of year: Zn (234)
--light: Rb (153)
--inorganics: Cd (44)
--organics: Cd (44); Ce (176); Co (123); Cr (123); Fe (123); Mn (123); Mo (153); Rb (153); Zn (11, 123).

Biochemical, morphological, and other sublethal effects:
-proteins: Co (26)
-cell volume: Co (26)
-Ca metabolism: Co (26)
-cell structure: Co (26); Hg (107)
-accelerates K release: Cu (150)
-cell permeability: Cu (150)
-non-mutagenesis: Pb (94)
-detoxification mechanisms: Hg (52, 53)
-motility: Pb (93)

Field Studies

Residues: As (27, 116, 154); Cd (65, 91, 116, 124, 193, 194); Co (177); Cr (65, 160, 177); Cu (65, 91, 177, 193, 194); Fe (65, 177); Hg (86, 91, 116, 188, 193); Mn (65, 177); Mo (177); Ni (65, 177); Pb (65, 91, 193, 194); Po (45); Pu (144, 183); Sb (116, 198); Ti (177); V (177); Zn (65, 91, 116, 177, 193, 194, 228)
-Modifiers:
--distance from point source: Cd (91, 116); Hg (91, 188); Zn (91)
--relation to water levels: Cd (65, 124); Mn (65); Ni (65); Zn (65)
--inorganics: Cr (177)
--age of organism: Cu (91); Zn (91)
--season of year: Cu (91); Zn (91)
--differential uptake of chemical species: Pu (144)
--species differences: Ti (177)
Food chain amplification: Hg (188)
Role in cycling: Zn (228)

ANNELIDA

Laboratory Studies

Survival: Cd (1, 168); Cr (148, 149, 168); Cu (34, 104, 131, 134, 168); Hg (168); Pb (168); Zn (1, 34, 168)
-Modifiers:
--age of organism: Cd (168); Cr (168); Cu (168); Hg (168); Pb (168); Zn (168)
--chemical species: Cr (148, 149)
--salinity: Cu (104)
Uptake, retention, translocation: Ag (34); Am (16); Cd (211); Co (6); Cr (148); Cu (134); Pu (16,67)
-Modifiers:
--reflection of substrate: Ag (34); Am (16); Cu (34); Pb (34); Zn (34)
--tissue specificity: Co (6)

--organics: Cu (134)
--chemical species: Pu (67)
Food chain transfer: Co (6)
Reproduction: Cr (148, 149)
Behavior:
-tube building: Cr (149)

Field Studies

Residues: Cr (160)
-Modifiers:
--diet: Cr (160)
--reflection of substrate: Cr (160)

BACTERIA

Field Studies

Isolation of resistant strains: Hg (41, 141)
Seasonal abundance: Hg (41)
-Modifier:
--correlated with oxygen: Hg (141)
Role in cycling: Cd (130); Zn (130)

BIRDS

Field Studies

Residues: Hg (111, 145); Se (111)
-Modifiers:
--age: Hg (111)
--inorganics: Hg (111); Se (111)
--diet: Hg (145)

BRYAZOA

Laboratory Studies

Growth and Development: Cd (58); Mg (58)

CHAETOGNATHA

Field Studies

Residues: As (28); Cd (28); Cu (28); Fe (28); Zn (28)

COELENTERATA

Laboratory Studies

Survival: Cu (135)
-Modifier:
--pretreatment sensitizes: Cu (136)
Growth: Cd (136, 191); Cu (136, 191); Hg (136, 191)
Uptake, retention, translocation: As (163)
Respiration: As (25)
Mucous production: Cu (135)
Interference with enzyme staining response: Cd (136); Cu (136); Hg (136)
Bacterial interaction: Cu (135)

Field Studies

Residues: Am (143); Bi (143); Co (143); Cs (143); Eu (143); Pb (143); Po (143); Pu (143); Rh (143); Sb (143); Sr (143); Y (143)
Discrimination among chemical species: Pu (143)

CRUSTACEANS

Laboratory Studies

Survival: B (205); Cd (1); Pb (171); Zn (1)
-Modifiers:
--salinity: B (205); Cd (98)
--temperature: Cd (98)
Uptake, retention, translocation: Ag (164); B (205); Cd (69, 98); Co (7, 8); Pb (171); Pu (67); Se (70, 71)
-Modifiers:
--tissue specificity: Ag (164); Cd (98); Co (8); Se (71)
--temperature: Cd (69, 98)
--salinity: Cd (98)
--inorganics: Cd (69)
--molting: Pu (67); Se (70)
--chemical species: Pu (67)
Respiration: As (25)
Food chain transfer: Co (6, 7, 8); Pu (67); Se (70, 71)
Protein synthesis: Pb (51)

Field Studies

Residues: Ag (18, 85); As (27, 28, 85, 154); Cd (18, 28, 85, 124, 193, 194, 197, 229); Ce (152); Cr (85); Cs (152); Cu (18, 28, 85, 99, 193, 194, 197, 229); Fe (18, 28); Hg (54, 84, 85, 110, 145, 188, 194, 197, 215, 227);

Mn (18, 99); Nb (152); Ni (18, 85, 229); Pb (18, 85, 99, 193, 194, 197); Po (95); Pu (89, 183); Ru (152); Sb (198); Zn (18, 28, 85, 99, 193, 194, 197, 218, 229); Zr (152)
-Modifiers:
--metabolism: As (27)
--diet: As (27)
--reflect substrate levels: As (154); Cd (124); Zn (218)
--age of organism: Cd (18); Po (95)
--tissue specificity: Cs (152); Hg (54); Po (95)
--monthly variation: Cs (152)
--seasonal and latitudinal variations: Cu (99); Hg (54); Mn (99); Pb (99); Zn (99)
--yearly fluctuations: Hg (215)
--niche in water column: Hg (110)
--organism complexity: Pu (183)
Food chain transfer: Hg (188)
Role in cycling: Po (95)
Non-hazard to man: Pu (89)

ECHINODERMATA

Laboratory Studies

Survival: Cu (92)
Growth: Cu (92)
Reproduction:
-Essential for successful reproduction: Mg (180)
-Fertilization success: Cu (92)
-Sperm motility: Cd (137); Co (137); Cu (137, 233); Fe (137); Hg (137, 233); Mn (137, 233); Ni (137); Sr (137); Zn (137, 233)
-Sperm motility modifiers:
--chelators: Cu (92); Hg (233); Mn (233); Zn (233)
--nucleoside phosphates: Cd (137); Cu (137); Fe (137); Hg (137); Mn (137); Ni (137); Zn (137)

Field Studies

Residues: As (154); Cd (63, 193); Cu (63, 193); Hg (110); Mn (63); Pb (193); Pu (183); Zn (63, 193)
-Modifiers:
--distance from point source: As (154)
--feeding niche: Hg (110)
--tissue specificity: As (154)

FISH

Laboratory Studies

Survival: B (205); Cd (139, 214, 224, 225); Cr (139, 186); Cu (120); Hg (109, 133, 222); Zn (120, 139)
-Modifiers:
--salinity: B (205); Cd (224, 225)
--chemical species: Cr (139); Hg (133, 156, 157)
--age of organism: Cu (120)
--temperature: Zn (139)
Uptake, retention, translocation: Ag (164); B (205); Be (59); Cd (37, 59, 175, 224, 225); Co (59); Cu (59); Hg (37, 133, 156, 157, 169); Mn (155); Ni (59); Sr (4); Zn (59, 155)
-Modifiers:
--sediment type: Cu (181); Sr (4)
--salinity: Hg (169); Sr (4)
--temperature: Sr (4)
--inorganics: Hg (169); Sr (4)
--mode of administration: Zn (170)
Growth and Development: Cd (175, 224, 225); Cu (181)
-Modifiers:
--inorganics: Cd (175)
--organics: Cd (175)
--chemical species: Cd (175)
--salinity: Cd (224, 225)
Behavior:
-sluggishness: Hg (109)
-uncoordinated movements: Hg (109); Zn (139)
-negative phototaxy: Hg (109)
-feeding response: Cr (186)
-migration: Cu (120)
-pigmentation change: Zn (139)
Histopathology: Ag (78); Cd (78); Cu (78); Hg (78); Zn (78)
Respiration: As (25); Cd (37, 214); Hg (37, 109)
-Modifier:
--salinity: Cd (214)
Heartbeat rate: Cd (224)
Fin erosion and regeneration: Cd (222); Pb (222); Zn (139)
Food chain transfer: Cu (181); Mn (155); Hg (156); Zn (155, 170)
Blood chemistry: Cd (37, 115); Hg (37)
Enzymes: Cu (120); Hg (169)
Hepatic binding proteins: Cd (147)

Field Studies

Residues: Ag (85, 127); Al (127); Am (158); As (27, 28, 85, 108, 116, 154); Cd (28, 33, 63, 85, 90, 116, 127, 193,

194, 197, 201, 229, 231); Ce (152); Cr (33, 85, 127, 160); Cs (152); Cu (28, 33, 63, 85, 127, 193, 194, 197, 201, 229); Fe (28, 33, 127); Hg (13, 46, 54, 61, 77, 84, 85, 110, 116, 145, 146, 165, 187, 190, 193, 194, 197, 201, 231); Mn (33, 63); Nb (152); Ni (33, 85, 127, 229); Pb (3, 33, 39, 85, 90, 127, 194, 197, 201); Po (96); Pu (89, 142, 158, 183); Ru (152); Sb (116, 198); Ti (127); Zn (28, 33, 63, 85, 90, 116, 127, 193, 194, 197, 201, 228, 229); Zr (152)

-Modifiers:
--tissue specificity: Al (127); Cd (33); Cr (127); Cu (63); Fe (127); Hg (13); Ti (127)
--associated with fin damage: Al (127); Cd (127); Cr (127); Fe (127); Ti (127)
--associated with changes in body elemental composition: Cd (127); Cu (33); Fe (33); Mn (33); Zn (33)
--seasonal variations: Am (158); Hg (85); Pu (158)
--age or size of fish: As (27, 28); Cd (28); Cu (28, 33); Fe (28, 33); Hg (54, 77, 145, 201); Mn (33); Zn (28, 33, 90)
--metabolism of fish: As (27)
--diet: Cd (90); Cu (63); Hg (110, 145, 165); Pb (90); Po (96); Pu (89); Zn (63, 90)
--reproductive state: Cu (64); Zn (64)
--sediment substrate: Hg (54, 110)
--depth of water column: Hg (85)
--geothermal activity: Hg (187)
--sex: Hg (54)
--distance from point source: Hg (146)
--geographic variations: Hg (85); Pb (3)
--chemical species: Pu (183)
--salinity: Cu (64); Zn (64)
Food chain amplification: As (108); Hg (190)
Contamination during canning process: Pb (39)
Role in cycling: Zn (228)

HIGHER PLANTS

Laboratory Studies

Survival: Cu (57); Pb (57)
Growth: Cu (57); Pb (57)

Field Studies

Residues: Cd (57); Co (177); Cr (177); Cu (57, 177, 194); Fe (177); Hg (118, 209, 227); Mn (177); Mo (177); Ni (177); Pb (15, 57); Ti (177); V (177); Zn (177, 194)

-Modifier:
--reflection of substrate: Cr (177); Fe (177); Mn (177); Ti (177)
Growth: Cd (132); Pb (132); Zn (132)
Food chain: Hg (118)
Role in cycling: Cd (57); Cu (57); Hg (209, 227); Pb (15, 57); Zn (228)

INSECTA

Field Studies

Residues: Ag (18); Cd (18); Cu (18); Fe (18); Hg (146); Mn (18); Ni (18); Pb (18); Zn (18)
-Modifiers:
--time: Fe (18)
--feeding substrate: Hg (146)
--diet composition affects retention time: Hg (146)
--growth stage: Ni (18)

MAMMALS

Field Studies

Residues: Ag (125); As (9); Cd (9, 35, 97, 125, 147, 172); Cu (97, 125); Fe (125); Hg (9, 35, 62, 79, 97, 103, 111, 125, 146, 172); Mg (125); Mn (125); Pb (9, 97, 172); Se (111, 125); Zn (97, 125)
-Modifiers:
--tissue specificity: Cd (9, 125, 147, 172); Cu (125); Hg (9, 35, 97, 103, 125, 172); Mn (125); Pb (9, 172); Zn (97)
--age of animal: Cd (172); Cu (125); Hg (9, 97); Mn (125)
--sex: Hg (103)
--sexual condition: Cd (125)
--tectonic activity: Hg (79)
--starvation: Hg (103)
--chemical species: Hg (79)
Health hazard: Hg (62, 146)
Reproduction: Cd (125); Cu (125); Hg (125); Mn (125); Se (125)
Hg detoxification aid: Se (111)

MOLLUSCA

Laboratory Studies

Survival: Ag (36, 140, 207); As (140); B (105); Cd (1, 140); Cu (24, 122, 195); Hg (36, 112, 140); Ni (36); Pb (36); Zn (1, 31, 36)

-Modifiers:
--salinity: Ag (207); Cu (122)
--age of organism: Cu (122)
--temperature: Cu (122)
--season: Cu (122)
Respiration: Ag (206, 207); Cd (140)
-Modifiers:
--salinity: Ag (207)
Uptake, retention, accumulation: Ag (164, 206, 207); As (140); B (205); Cd (140, 161, 235); Co (7, 8); Cu (23, 24, 161, 181); Hg (42, 43, 47, 48, 66, 112, 140, 182); Fe (80); Pb (161, 184, 196); Pu (67); Ru (100); Se (70, 71); Tl (236); Zn (49, 161)
-Modifiers:
--temperature: Cd (69, 161); Cu (161); Hg (47, 112); Pb (161); Se (71); Zn (161)
--salinity: Cd (161); Cu (161); Pb (161); Zn (161)
--inorganics: Cd (69, 161); Cu (161); Hg (66, 112); Pb (161); Se (171); Zn (161)
--tissue specificity: Co (7, 8); Cu (23); Hg (47, 48); Fe (80); Pb (184, 196); Pu (67); Ru (100); Se (70, 71)
--organics: Cr (14); Cu (14); Hg (14); Pb (14); Zn (14)
--chemical species: Cr (14); Cu (14); Hg (14, 48, 112); Se (71); Zn (14)
--role of bacteria: Hg (42, 43, 182)
--age of organism: Hg (47); Pb (184); Se (71)
--reproductive stage: Hg (47)
--particulates: Fe (234)
--mode of administration: Pb (184)
--initial concentration: Pb (184)
Reproduction:
-gametogenesis: Cu (122)
-birth defects: Hg (167)
-larval settling: Zn (31)
Behavior:
-valve movements: Ag (206)
-burrowing ability: Cu (195)
--modified by chelators: Cu (195)
-feeding rate: Hg (55)
Histology: Cu (24); Hg (66); Fe (80)
Growth: Cu (122, 181); Pb (196); Zn (31)
Health hazards: Cd (235); Hg (112)
Food chain transfer: Cd (69); Co (7, 8); Cr (14); Cu (14, 181); Fe (234); Hg (14, 48); Pb (14, 184, 196); Zn (14, 234)
Seasonal dynamics: Cd (75); Co (75); Cr (75); Cu (75); Fe (75); Mn (75); Ni (75); Pb (75); Zn (75)

Field Studies

Residues: Ag (2, 10, 74, 86, 126, 219, 220); As (27, 116, 121, 154); Bi (220); Cd (10, 29, 63, 74, 76, 86, 116, 121, 126, 161, 162, 165, 192, 193, 194, 203, 212, 219, 220, 231); Ce (152); Co (74, 220); Cr (2, 10, 74, 160, 220, 232); Cs (152); Cu (2, 10, 22, 29, 30, 56, 63, 74, 76, 86, 121, 126, 161, 162, 165, 174, 192, 193, 194, 219, 220, 232); Fe (29, 74, 76, 126, 174, 219, 220); Hg (10, 77, 86, 110, 116, 193, 194, 227, 231); Mn (63, 74, 76, 194, 219, 220); Ni (2, 10, 29, 74, 194, 219, 220, 232); Pb (2, 10, 29, 40, 74, 86, 121, 161, 162, 193, 194, 212, 220); Pu (183); Ru (152); Sb (116, 198); Zn (2, 10, 29, 30, 56, 63, 74, 76, 86, 116, 121, 126, 161, 162, 165, 174, 192, 193, 194, 212, 219, 220, 232)

-Modifiers:

--distance from point source: Ag (2); As (154); Cd (165); Cr (2); Cu (2, 165, 232); Hg (10); Pb (2,40); Zn (165, 232)

--latitude: Ag (10); Cu (10)

--seasonal variations: Ag (74); Cu (22, 74, 76)

--inorganics: Ag (126); Cd (126); Fe (126); Zn (126)

--age of organism: Ag (220); As (121); Bi (220); Cd (29, 121, 220); Co (220); Cr (220); Cu (29, 121, 220); Fe (29, 220); Mn (220); Ni (29, 220); Pb (29, 121, 220); Zn (29, 121, 220)

--body weight: As (121); Cd (121); Cu (29, 121)

--sex: Ag (220); Bi (220); Cd (220); Co (220); Cr (220); Cu (220); Fe (29, 220); Mn (220); Ni (220); Pb (220); Zn (220)

--tissue specificity: As (116); Cd (86, 116); Cu (86); Hg (116); Sb (116); Zn (116, 218)

--water depth: Cd (161); Cu (161); Pb (161); Zn (161)

--reflects substrate composition: Cd (76, 192); Cu (76, 192); Fe (76); Mn (76); Zn (76, 192)

--seasonal variations: Cd (74, 76); Co (74); Cr (74); Fe (74, 76), Mn (74, 76); Ni (74); Pb (74); Zn (74, 76)

--particulates: Ce (152); Cs (152); Ru (152)

--diet: Cr (160); Hg (110)

--contamination from test pump: Cu (30); Zn (30)

Growth: Cd (212); Pb (212); Ra (210); Zn (212)

Role in cycling: Hg (227)

NEMATODA

Laboratory Studies

Uptake: Pb (171)

PLATYHELMINTHES

Laboratory Studies

Uptake: Pb (171)

PROTOZOA

Laboratory Studies

Reproduction: Cd (159); Cu (159); Hg (159); Pb (159); Zn (159)
Growth: Hg (82); Pb (82); Zn (82)
-Modifier:
--inorganics: Hg (82); Pb (82); Zn (82)

TUNICATA

Laboratory Studies

Uptake, retention, accumulation: V (113, 129)
-Modifiers:
--tissue specificity: V (113)
--organics: V (129)
--inorganics: V (129)

Field Studies

Residues: As (116); Cd (63, 116); Cu (63); Hg (116); Mn (63); Sb (116); V (202); Zn (63, 116)
-Modifiers:
--chemical species: V (202)